Working memory load affects early affective responses to concrete and abstract words differently: Evidence from ERPs

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Abstract

Early posterior negativity (EPN) is an early-occurring, event-related, potential that is elicited by pictures and words that have highly arousing characteristics. Whilst EPN has been found with words presented in isolation several times, different types of words have shown quite different effects across different types of tasks. One possible reason for this is that memory and attentional demands may affect the way semantic features of words are processed, and this may modulate EPN. This was investigated in a silent reading task using abstract and concrete words of negative and neutral valence and a dual phonological working memory task to manipulate memory load. The results showed that abstract but not concrete words elicited EPN, and this may have affected downstream processing. Further analyses examining alpha desynchronization showed that negative concrete words appeared to be significantly affected by the memory load manipulation, unlike negative abstract words. These results provide evidence that the processing of features in negative concrete words is more affected by working memory and attentional demands than the processing of features in negative abstract words, and this may be responsible for the failure of negative concrete words to elicit EPN in this study. Thus, the extent to which words elicit EPN appears to be dependent on both their semantic representations and competing cognitive processes. These results provide a potential explanation for some of the differences that have been reported in previous experiments as well as insight into how memory and attention can affect the processing of the semantic features of words.

Keywords Early posterior negativity · Concreteness · Emotion · Working memory · Reading

An early-occurring effect caused by affective stimuli that has been found with electroencephalography in both reading and picture tasks is known as early posterior negativity (EPN) (Olofsson, Nordin, Sequeria, & Polich, 2008; Schupp, Junghöfer, Weike, & Hamm, 2004; Kissler, Herbert, Peyk, & Junghofer, 2007). This effect peaks between 200–300 ms after stimulus presentation, has an occipito-temporal scalp distribution, and its amplitude is larger for highly arousing compared with neutral stimuli. It is thought to occur due to the increased

motivational significance of emotional stimuli and has been associated with the initial, automatic stages of attentional orientation and capture (Schupp et al., 2004; Kissler et al., 2007). Significant EPN effects have been reported across a variety of reading tasks, including silent reading (Herbert, Junghofer, & Kissler, 2008; Kissler et al., 2007; Kissler, Herbert, Winkler, & Junghofer, 2009), lexical decision (Palazova, Mantwill, Sommer, & Schacht, 2011; Schacht & Sommer, 2009; Scott, O'Donnell, Leuthold, & Sereno, 2009), identifying words in a stream of words/pseudowords (Hinojosa, Méndez-Bértolo, & Pozo, 2010), and the emotional Stroop task (Franken, Gootjes, & van Strien, 2009).

Apart from being associated with attentional capture, a less well-understood aspect of processes associated with EPN is how they affect later downstream processing. Kissler and Herbert (2013) and Keuper et al. (2012) have suggested that these processes may cause facilitated lexical and semantic access, which Keuper et al. (2012) suggested may work via “emotional tagging.” This idea has been previously discussed in studies

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examining pictures (Olofsson et al., 2008) and suggests that EPN may be associated with the preferential selection of arousing features for further processing. Thus, processes causing EPN may not only cause words to be processed faster but also may cause qualitative changes in their processing.

One way to investigate the downstream effects of processes associated with EPN is to examine the extent to which they modulate the N400 and Late Positive Components (LPCs; see below for a summary of a number of studies). The N400 is a well-established marker of semantic processing (Kutas & Federmeier, 2011), and effects of emotion on semantic processing have been commonly reported in both single word and sentence studies (Herbert et al., 2008; Parkes, Perry, & Goodin, 2016). In general, unlike words of neutral valence, where semantic effects are very robust, more variable effects have been found with emotion words. This suggests that the semantic processing of emotion words may differ compared with neutral words. Effects of emotion on LPCs also have been mixed. When differences have been found, it has been suggested that they are due to the evaluation of the emotional characteristics of the words (Cao, Yang, & Wang, 2018). Explanations of particular processing dynamics have also been offered, such as the role of attentional capture on top-down processing (Carretié et al., 2008).

What modulates EPN and other effects of emotion with words?

It is interesting to consider what might modulate early emotional processing in word-reading tasks (Kissler et al., 2009) and how this might affect downstream processing. In this respect, an important variable that has been investigated is concreteness (Kanske and Kotz, 2007), which allows the effect of emotion on semantic processing to be examined. The results from different studies have been quite mixed. When lexical decision tasks have been used, some studies have found that negative concrete words show greater differences compared with neutral control words than negative abstract words do. Such a result was found by Xu et al. (2017) and Palazova et al. (2013), who both found early differences between emotional concrete and neutral words (Xu et al.: 250–350 ms; Palazova et al.: 250–300 ms) but not between emotional abstract and neutral words in the same time windows. Note that Xu et al.'s results showed no effect of EPN, although this is unsurprising given that they used an average mastoid reference and EPN is typically found with an all-average reference (Olofsson et al., 2008). Both studies also found an effect of emotion with abstract words on the N400. However, Xu et al. found that topographic differences between emotional and neutral words were very restricted for abstract compared with concrete words, whereas Palazova et al. found that topographic differences were quite broadly distributed for both types of words.

Finally, in terms of LPC effects, Xu et al. did not find any significant effects, whereas Palazova et al. reported a main effect of concreteness as well as a main effect of emotion that was significant in only some of the consecutive 50-ms blocks that were examined within their LPC time window.

A study by Yao et al. (2016) also used a lexical decision task to examine interactions between concreteness and emotion. They examined positive and negative words with an average mastoid reference and found somewhat different results than Palazova et al. (2013) and Xu et al. (2017). With concrete words, they found an effect of emotion on the N400 with positive but not negative words. They also found an effect of emotion on LPCs, where positive words showed a greater amplitude and negative words a lesser amplitude than neutral words. With abstract words, a N170 was found, with positive words showing a greater amplitude and negative words a lesser amplitude than neutral words. They also found an effect of emotion on the N400 with negative but not positive words, as well as on LPCs, with both negative and positive words producing a greater amplitude than neutral words.

Another study using lexical decision to examine emotion and concreteness was run by Kanske and Kotz (2007). Their task, however, was more complex than a simple lexical decision task, because it used a hemifield design. They found an early effect of emotion, which was restricted to positive words, but it was on the P2 component and not EPN. However, their study utilised an average mastoid reference, which, as previously noted, may explain the absence of EPN. This effect did not interact with concreteness. An effect of emotion also was found on the N400 with both negative and positive words, and this extended into their LPC window. Finally, they found a main effect of concreteness on the N400 and LPCs, but there were no interactions with emotion. In a second experiment, Kanske and Kotz examined emotional words with a go/nogo experiment after suggesting that their LPC responses in the lexical decision experiment could have been affected by the behavioral responses. In the new experiment, an interaction in their LPC window was found where there was an effect of emotion on concrete but not abstract words.

Compared with the previous studies, Kaltwasser et al. (2013) found a noticeably different pattern of results when they examined emotion words in a semantic categorization task. They failed to find EPN, despite using an all-average reference, and found an effect of emotion between 400 ms and 700 ms that was most pronounced with abstract words. Their results are thus quite different to Xu et al. (2017), Palazova et al. (2013), and Kanske and Kotz (2007) but more similar to those of Yao et al. (2016).

The most common reason suggested for differences in results between studies is that differing demands caused by task type are important (Kaltwasser et al., 2013; Palazova et al., 2013; Xu et al., 2017). Task demands also have been

implicated in null effects, with Hinojosa et al. (2010) explicitly showing how a difficulty manipulation affected EPN, and Hinojosa et al. (2014) offering it as a suggestion as to why they failed to find significant effects in their experiment. Kissler et al. (2009), alternatively, found EPN in both a silent reading and a noun counting task, even though noun counting might be considered relatively difficult. However, the reason noun counting is difficult may be important in explaining why it did not modulate EPN. In this case, determining the grammatical status of a word is likely to come after the initial processing of a word. Thus, it may not represent a strong difficulty manipulation with respect to its effect on early processing and hence may be less likely to interfere with early processing than some other types of task difficulty manipulation. Overall, it seems reasonable to suggest that task demands are likely to be important, with greater demands potentially leading to reduced effects and deviations from the typical pattern where concrete words show larger effects than abstract words.

Modulating task demands

One way that the resources available for early word processing can be manipulated is via the use of a dual working memory task (Pashler, 1994). Using such a manipulation allows task effects to be examined that could affect even the earliest aspects of word processing (and hence EPN). In addition, if all processes in reading that occur after lexical access use memory and attention (Reynolds & Besner, 2006), then increasing memory load may interfere with the generation of EPN via a reduction in the extent to which the representations of words, including their affective features, are processed.

Predictions about the effect phonological working memory load has on EPN can be made with different types of words. According to Dual-coding theory (Paivio, 1986), the extent to which visual and verbal information is used to learn the representations of abstract and concrete words differs, with abstract words more heavily loaded on verbal than visual information compared with concrete words. If learning leaves associations between word representations and the contexts in which they were learnt in, one might expect abstract words to be affected more by phonological working memory load than concrete words. In this case, because a phonological working memory load task would use the same working memory resources that are used when reading, it may reduce the reading performance of abstract words more than concrete words due to abstract words potentially being more reliant on these shared working memory resources.

Kousta et al. (2011) and Vigliocco et al. (2014) offer a different suggestion to the Dual-coding theory about how the representations of words are structured. They suggested that concrete words tend to be linked to sensory-motor

information, whereas abstract words are derived via metaphorical extension to concrete words and include affective representations, with linguistic information not necessarily being the primary form of representation. Thus, whilst there are likely to be differences in the statistical properties of abstract and concrete words with respect to their feature distributions, the differences are less clear than the Dual-coding theory. Given this, the extent to which phonological working memory load may affect the processing of abstract words differently to concrete words is less clear.

How concrete and abstract words with emotional valance are processed is also of interest. Compared with neutral concrete words, emotional concrete words would need to have additional affective features; otherwise they would not be emotional. Thus, their feature distribution must differ from neutral words, having more affective/linguistic representations. Emotional abstract words also must have additional or stronger affective associations compared with neutral abstract words but need not have additional sensory-motor features. Thus, emotional concrete words are likely to have the most mixed distribution of features compared with emotional abstract and neutral words, having a combination of sensory-motor, linguistic, and affective representations. The actual distribution of these features may be important in terms of how these words are processed, because groups of features that are related can affect processing depending on the extent to which the features are similar (Hoffman & Woollams, 2015). In this case, the effect of groups of individual features is not necessarily simply the sum of the individual features.

One final way that emotional abstract words may differ from emotional concrete words is the extent to which their features differentially activate areas of the brain thought to be important in emotional processing. Vigliocco et al. (2014) provided evidence for this after finding that, compared with other types of words, highly valenced abstract words produced unique activation in rostral anterior cingulate cortex, an important area for some types of emotion processing. If affective features that cause this can be activated early in processing, they may potentially prioritize further processing compared to other stimuli (Pessoa, 2009). Thus, highly valenced abstract words may be less affected by memory load than highly valenced concrete words.

This study

The present study investigated the extent to which EPN can be modulated by high and low working memory demands in a silent reading task using words presented in isolation, and the effect this has with abstract and concrete words of neutral and negative valence. This was examined using standard ERPs as well as alpha desynchronization. Alpha desynchronization was used, so more specific information about the effect of

memory load and the processing of semantics could be examined. In particular, both lower alpha (i.e., alpha below 10 Hz) and upper alpha (alpha above 10 Hz) power are thought to be markers of different types of processing (Klimesch, Doppelmayr, & Hanslmayr, 2008; Klimesch, Sauseng, & Hanslmayr, 2007). According to Klimesch et al. (2007), desynchronization of lower alpha is a marker of increased memory and attentional demands, and desynchronization of upper alpha is a marker of semantic processing. Both of these factors are important in our task. Results from alpha desynchronization thus allow particular types of processing to be examined that are complementary with ERPs and potentially offer simpler interpretations by helping to dissociate effects that might otherwise overlap.

Apart from EPN, we were interested in downstream processing effects. Both concrete and abstract words allow this to be examined, because they potentially behave differently based on differing task demands, as summarized above. It is important to use such a manipulation, because it allows effects of emotion on the N400 and LPCs to be examined in a way that could not be found by examining emotion without such a manipulation. Specifically, if the difference between affective abstract and concrete words is less than neutral abstract and concrete words on markers such as the N400, then this would suggest that they are processed differently and that this is due to the effect of emotion.

In terms of predictions, with the ERPs, if EPN is automatically generated, we would expect that it should be found with negative words and be independent of working memory demands. Alternatively, if EPN is not automatic, it should be reduced in the high compared with low memory load condition. Effects of EPN may carry on to later stages of processing. In this case, if there are qualitative changes caused by processes associated with EPN whereby emotional features are prioritized (Olofsson et al., 2008), then differences between concrete and abstract words may differ compared with those that would otherwise be found in the N400 and LPC windows. In terms of lower alpha desynchronization, the high load condition should display more desynchronization than the low load condition. More importantly, based on the idea that feature distribution is important (Hoffman & Woollams, 2015), negative concrete words may show more desynchronization than other types of words in high load conditions, because they may need more memory and attentional resources to process. Later effects of emotion may be found if the processing of emotional information allows the acquisition of additional attentional resources compared with the processing of neutral information (Vuilleumier, 2005). In this case, processes associated with EPN may lead to greater processing resources being acquired for reading from the competing dual phonological working memory task with negative compared with neutral words. Finally, in terms of predictions for upper alpha desynchronization, we would expect early semantic processing differences between negative concrete and neutral words to appear based on the findings of Hoffman and Woollams

(2015). Given that semantic processing is reliant on working memory and attentionally demanding when reading (Reynolds & Besner, 2006), there may be less desynchronization in the high load condition due to increased difficulties related to semantic processing.

Methods

Participants

Participants consisted of 24 healthy individuals (11 males and 12 females; 1 participant did not answer this question) who were between 20 and 30 years old. They were either Swinburne undergraduate students or people known to the experimenters who were recruited via word of mouth. As indicated by self-report, three participants were left-handed, and all participants were (a) native English speakers; (b) had normal or corrected to normal vision; (c) did not suffer from any neuropsychological disorders; and (d) were not taking any psychiatric medications. Participants were recruited after the study had received ethics clearance from Swinburne University's ethics board (SHR Project: 2016/052).

Stimulus material

The stimuli used in the present study were 860 words that were selected from the Warriner, Kuperman, and Brysbaert (2013) database. Further statistics were generated from the English Lexicon Project (Balota et al., 2007). Of these, 560 were target words and 300 were fillers. Twenty additional practise words were used at the beginning of the task. The target words were divided equally into four groups defined by emotion (negative or neutral) and concreteness (abstract or concrete). The four groups were matched on bigram frequency, word frequency, log word frequency, orthographic neighbourhood (Coltheart, 1977), mean bigram frequency, word length, reaction time in a naming task, and error rate in a naming task (Table 1). The two groups of concrete words had scores matched on concreteness, as did the two groups of abstract words ($ps > 0.1$). Similarly, the two groups of negative words had scores matched on emotional valence as did the two groups of neutral words ($ps > 0.1$). Alternatively, the concrete and abstract words differed significantly on concreteness, as did the neutral and negative words on emotional valence ($ps < 0.0001$). The negative words also differed significantly compared with the neutral words on arousal ($ps < 0.0001$).

The word groups were further split into two different counterbalanced groups. This was done by dividing the target words in each of the four possible conditions that can be created from the concreteness (abstract/concrete) and emotion

Table 1 Mean lexical characteristics of the target words

Word group	Example	Valence	Arousal	Concreteness	Word frequency	Log word frequency	Word length	Orthographic neighbors	Bigram frequency	RT	Error rate (%)
<i>Concrete</i>											
Negative	Maggot	2.51	5.39	4.24	410	2.05	7.71	1.63	3862	681	3.60
Neutral	Trailer	4.80	3.17	4.33	388	2.13	7.37	2.00	3880	689	2.48
<i>Abstract</i>											
Negative	Neglect	2.59	5.27	1.97	375	2.15	7.54	1.25	4162	686	2.46
Neutral	Context	4.78	3.10	2.04	303	2.11	7.47	1.44	3840	676	2.43

Note: RT = reaction time

(negative/neutral) factors into two further groups, leading to eight groups. In each counterbalanced group, all words were always presented. However, half of the words (all words from 4 of the new groups) were presented in a high memory load condition, and the other half (all words from the other 4 groups) in a low memory load condition, with the groups being chosen so that each counterbalanced group had equal numbers of stimuli from each condition (i.e., 70 words in each cell of a 2 Concreteness $\times$ 2 Emotion $\times$ 2 Memory load design). The words presented in the low memory load condition in one counterbalanced group were the same words presented in the high memory load condition in the other counterbalanced group, and vice-versa. Participants were assigned to either the first or second counterbalanced group based on when they did the task. That is, the first participant was given the first list, the second was given the second list, and the list given continued to alternate with each new participant. In terms of the filler words, all were randomly sampled from the same database, excluding those words with a valence score less than 3.2.

Task description

Participants were seated comfortably in a dimly lit room in front of a computer screen. They were given information about the study and were asked to read and fill out an informed consent form. After this, the electrode cap was applied, verbal instructions were given on the nature of the task, and each individual was given the opportunity to ask questions. In particular, a description of the task was given to them where they were told they would be presented with a list of numbers to remember whilst they silently read words that appeared. All participants were instructed to keep as still as possible whilst engaging in the reading aspect of the task and to move only if they needed to when entering the numbers as part of the memory task. They also were informed that participation was completely voluntary, and they could withdraw at any time. To present the stimuli, E-prime software version 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA) was used.

For the memory task (see Figure 1 for the entire sequence of events), participants were presented with a string of six

numbers that were either all the same (e.g., 666666) or different (e.g., 659712), which they were asked to remember. They were then presented with the words sequentially and prompted to enter the numbers that they were presented with at the end of the trial.

The words were presented in a pseudorandom order, with no two in the same category following each other. Each block of trials that occurred between the memory load task consisted of 8–12 words. Words were presented in a white 18-point font for 500 ms in the middle of a black screen. After the presentation of each word, the screen remained blank for 1,200 ms. In terms of the memory task, the list of numbers was presented for 3 seconds, which was then followed by a blank screen for 3 seconds. Following the presentation of the words, the participant was given a prompt where they were asked to type in the numbers that they remembered from the start of the trial. After the participant had typed in the numbers and pressed the enter button, a blank screen was presented for 2 seconds, and the next trial began.

EEG recording and data processing

The electroencephalogram (EEG) recordings were obtained using a NeuroScan System SynAmps RT amplifier on a Dell

Fig. 1 Stimulus presentation sequence

Optiplex 780 computer screen. The EEG was recorded using a cap consisting of 64 Ag-AgCl electrodes (International 10/10 System, NeuroCap) sampling at 1,000 Hz. The EEG data was referenced to linked mastoids while AFZ served as the ground. The impedance of all electrodes was kept below 5 kilo-ohms, excluding the CB1 and CB2 electrodes, which we intended to discard a priori. The EEG was located in an electronically shielded room at Swinburne University of Technology. The EEG signal was recorded using NeuroScan 4.3 software.

The data was pre-processed and analysed offline using Fieldtrip (Oostenveld, Fries, Maris, Schoffelen, 2011) with MATLAB (R2016a). Initially, the CB1 and CB2 electrodes were removed from the analysis, and the data were visually inspected for bad channels. One subject had 4 bad channels, which were reconstructed using the average values of other channels found via Fieldtrip's triangulation method with a neighbourhood distance of 2. A 35-Hz low pass filter was then applied to the data. Following this, target trials were extracted for each word from −300 ms to 1,200 ms. Independent Component Analysis (ICA, runica algorithm) was then run to decompose the data. Components identified by the ICA were checked, and any that appeared to represent eye movement artifacts, blinks, impedance related artifacts, cardiac rhythm, and any other notable muscular movement were removed. The data were then recalculated to an all-average reference and put through a two-stage procedure to automatically identify bad trials. In the first stage, trials were rejected based on being over various criteria derived from Fieldtrip's visual data inspection tool. These included: variance (2,000), range (250), maximum absolute difference (150), maximum Z score (10), and kurtosis (10). Following this, further trials were excluded if they fell 4 SDs above the mean variance, range, maximum absolute difference, or maximum Z scores. This procedure caused two participants to have excessive trials eliminated despite normal looking data. Therefore, we increased the maximum absolute difference threshold of one of the participants to 200 and the kurtosis threshold of the other to 12 to reduce the number of trials eliminated. Overall, 9.7% of the data was removed. Of the manipulations of interest, 9.3% and 9.9% of the negative and neutral words, 8.8% and 10.5% of words in the high and low load memory condition, and 9.9% and 9.4% of the abstract and concrete words were removed.

The remaining data were examined two different ways. First, we examined the ERPs relative to a 150 ms prestimulus baseline. Second, we examined the extent of alpha desynchronization in the data. This was done by first duplicating 500 ms from the start and end of each trial (i.e., from −300 ms to 200 ms and 700 ms to 1,200 ms where the onset of the trial is at 0), reversing the direction of these segments, and then attaching them to the start and end of each trial, creating a trial length of 2,200 ms. This was done to reduce edge effects (Cohen, 2014). After this, a firsl bandpass filter was

performed on the data using a range of 8–10 Hz (lower alpha) and 10–12.5 Hz (upper alpha). The analytical signal from each trial was then extracted (Knösche & Bastiaansen, 2002), and an envelope was created around each of them using the Matlab *hilbert* command. The envelopes were then used for further analyses after the two 500 ms duplicated sections were removed. Trials were then baseline corrected based on the average absolute amplitude of the envelope between −150 ms and stimulus onset for the high and low memory load conditions separately. Different baselines were used, because there were differences between the groups that existed before the onset of the trials due to the memory load manipulation. That is, because the high and low memory load manipulation occurred across the presentation of the words, it caused greater desynchronization in the high load than the low load condition, including when no words were presented. Thus, if the stimuli were baseline corrected without taking this into account, it would remove part of this effect rather than just removing random fluctuations that occurred before stimuli onset.

Examining the data

To examine the data, we used cluster-based permutation tests (Maris & Oostenveld, 2007) as implemented in Fieldtrip. In terms of options, we examined each data point and used a two-tailed distribution. In terms of comparisons, we examined the three main effects (emotion, memory load, and concreteness) as well as interactions. When these were significant, we considered other testing to be post-hoc. To correct the *p* values of the post-hoc testing, we only accepted a difference as significant after a Bonferroni correction for multiple comparisons.

Because the cluster-based permutation method is sensitive to the time window that the data is examined in, based on inspection of the data and a priori knowledge about EPN, we first examined the data in a short window between 250–350 ms. Using windows is necessary, because the statistical method used only allows significance to be interpreted between conditions specified by the window, despite detailing when certain clusters within the time range are significant. Thus, using a longer range would not allow us to determine if an effect of emotion was related to, for example, an EPN or N400 effect (e.g., http://www.fieldtriptoolbox.org/faq/how_not_to_interpret_results_from_a_cluster-based_permutation_test). In a second analysis, we used a more exploratory window between 350–650 ms, which was designed to examine semantic processing associated with N400 and LPC effects that may overlap it. Finally, a late window of 650–1,100 ms was used to examine processing after the N400 with the ERPs, and a window of 650–1,000 ms was used with the alpha desynchronization data to avoid edge effects. Note that there is no reason to expect the time-course of the

alpha desynchronization results and how they correlate with the effects of interest to be identical to the ERPs, and the 350–650 ms window used with the ERPs is likely to be a mixture of N400 and LPC processing. However, for the sake of simplicity, we will use the terms EPN, N400, and LPC for the three windows.

Results

Behavioral data

The behavioural data was examined using a paired samples *t*-test on the accuracy rates from the low and high memory load conditions. A response was only considered correct if all the digits were the same as the original item. The results showed that participants were significantly more accurate in the low ($M = 96.3\%$, $SD = 2.5\%$) compared with high ($M = 69.4\%$, $SD = 18.1\%$) memory load condition ($t(23) = 7.50$, $p < 0.0001$).

ERPs

In the EPN window, the main effect of memory load was significant ($p = 0.0054$), with significant electrodes in the high load condition showing a more negative amplitude than the low load condition. There also was a significant emotion by concreteness interaction ($p = 0.042$). Based on this interaction, we examined the effect of emotion with the concrete and abstract words separately. Only the abstract words showed a significant difference ($p = 0.0008$), with significant electrodes found in both posterior and anterior regions. These showed the standard EPN pattern; the negative words had a more negative amplitude than the neutral words in the posterior region, and the opposite pattern was found in the anterior region. We also examined the effect of concreteness with the negative and neutral words separately. Only the negative words showed a significant difference ($p = 0.0056$), with the concrete words having a more positive amplitude than the negative words in the posterior region and the opposite found in the anterior region. The results appear in Figure 2 and the Supplementary Materials (Figs. S1–S3).

In the N400 window, significant main effects of all three variables were found (Emotion: $p = 0.0074$; Memory load: $p = 0.0498$; Concreteness: $p = 0.0044$). There also was a significant emotion by concreteness interaction ($p = 0.021$). Further post-hoc tests showed that the results were very similar to the EPN window. In particular, when emotion was examined with the concrete and abstract words separately, only the abstract words showed a difference ($p = 0.002$), and when concreteness was examined with the neutral and negative words separately, only the negative words showed a significant difference ($p = 0.0001$).

In the LPC window, there was a main effect of concreteness ($p = 0.022$) and a significant concreteness by emotion interaction ($p = 0.024$). Unlike the two earlier windows, post-hoc tests showed that the difference between negative abstract and neutral abstract words was not significant, although the negative words still showed a significant effect of concreteness ($p = 0.0017$) that was very similar to the two earlier windows.

Lower Alpha

There were main effects of memory load in all three windows (EPN: $p = 0.0022$; N400: $p = 0.0042$; LPC: $p = 0.010$) with the high memory load condition displaying more desynchronization than the low load condition. The two-way emotion by memory load interaction also was significant in the N400 window ($p = 0.035$), and the three-way emotion by concreteness by memory load interaction was significant in all three windows (EPN: $p = 0.011$; N400: $p = 0.015$; LPC: $p = 0.020$). The results appear in Fig. 3, and example electrodes appear in the *Supplementary Materials* (Fig. S4).

Further examination of the three-way interaction showed that it appeared to be caused by effects of emotion being largely restricted to concrete words and effects of memory load being largely restricted to negative concrete words. In terms of significance, post-hoc testing of emotion in the low and high load conditions showed significant differences in the EPN ($p = 0.0042$) and N400 ($p = 0.0032$) windows with the high load words, where negative words caused more desynchronization than the neutral ones, and an effect in the opposite direction in the low load condition in the LPC window ($p = 0.0038$). Further post-hoc testing of memory load showed a significant effect with the negative concrete words in all three time-windows (EPN: $p = 0.0002$; N400: $p = 0.0012$; LPC: $p = 0.0008$) where the negative concrete words caused more desynchronization in the high load compared with low load condition. More desynchronization also occurred in the high load compared to low load condition with the neutral abstract words in the EPN window ($p = 0.008$).

Upper Alpha

A significant emotion by concreteness interaction was found in the EPN window ($p = 0.014$). This appeared to be because the concrete and abstract words showed an effect in the opposite direction of each other; the negative abstract words showed more desynchronization than the neutral abstract words, and the opposite pattern was found with the concrete words. These results are displayed in Fig. 4, and example electrodes appear in the *Supplementary Materials* (Fig. S5). Further post-hoc testing showed neither the abstract nor concrete words showed a significant effect of emotion by themselves. In the N400 window, there was a main effect of

Fig. 2 Top panel: Significant differences represented as topographic maps. Topographic maps are averages from the time course of the most significant cluster. Significant electrodes from a representative single point of time are marked with a +. Numbers below the maps represent *p* values of significant clusters within the time-window examined. Difference scores represent: Emotion = Negative – Neutral, Memory load = High - Low, Concreteness = Abstract – Concrete. Concreteness by

Emotion interaction: Emotion difference with concrete words minus emotion difference with abstract words. Lower panel: Example ERPs from different electrodes. Note: A = Anterior; P = Posterior; HNeg = High load negative; LNeg = Low load negative; HNeu = High load neutral; LNeu = Low load neutral; HCon = High load concrete; LCon = Low load concrete; HAbs = High load abstract; LABs = Low load abstract

emotion ($p = 0.028$), as well as an emotion by concreteness interaction ($p = 0.043$) that was similar to the EPN window. Post-hoc tests showed that only the abstract words showed a significant effect of emotion by themselves ($p = 0.022$). Finally, in the LPC window, there was again a main effect of

emotion ($p = 0.035$). There also was an emotion by memory load interaction ($p = 0.036$). Post-hoc testing showed that the effect of emotion was only significant with words presented in the high load condition ($p = 0.0076$), with the negative words causing more desynchronization than the neutral ones.

Fig. 3 Top panel: Significant differences represented as topographic maps. Topographic maps are averages from the time-course of the most significant cluster based on envelope amplitudes. Significant electrodes from a representative single point of time within the significant cluster are marked with a +. Difference scores represent: Emotion = Emotion – Neutral, Mem = High – Low, Concrete = Abstract – Concrete. Memory load by emotion interaction: Difference between emotion with high load words minus differences between emotion with low load words. Three-way interaction = Difference in differences between high and low load

concrete words minus differences in differences between high and low load abstract words. Lower panel: Mean difference scores in the emotion (Negative – Neutral) and memory load (High – Low) conditions in each of the three time-windows based on envelope amplitudes derived from the FCZ electrode. Error bars are ± 1 SE. Note: Mem = Memory; HighAbs = High load abstract; LowAbs = Low load abstract; HighCon = High load concrete; LowCon = Low load concrete; NegAbs = Negative abstract; NegCon = Negative concrete; NeuAbs = Neutral abstract; NeuCon = Neutral concrete

General Discussion

Overall, the results were somewhat unexpected. With the ERPs, emotion differentially affected the processing of concrete and abstract words, with a concreteness by emotion

interaction found in all of the time-windows examined. Post-hoc testing confirmed that abstract words showed a significant effect of emotion in the EPN and N400 windows, including significant electrodes in both anterior and posterior areas, but concrete words showed no significant effects. A significant

Fig. 4 Top panel: Significant differences represented as topographic maps. Topographic maps are averages from the time-course of the most significant cluster based on envelope amplitudes. Significant electrodes from a representative single point of time are marked with a +. Difference scores represent: Emotion = Negative – Neutral, Mem = High - Low, Concrete = Abstract – Concrete. Emotion by memory load interaction: Differences between emotion with high load words minus differences between emotion with low load words. Lower panel: Mean difference

scores in the emotion (Negative – Neutral) condition in each of the three time-windows based on envelope amplitudes derived from the FC5 and PO5 electrodes. Error bars are ± 1 SE. Note: Mem = memory; HNegAbs = High load negative abstract; HNeuAbs = High load neutral abstract; HNegCon = High load negative concrete; HNeuCon = High load neutral concrete; LNegAbs = Low load negative abstract; LNeuAbs = Low load neutral abstract; LNegCon = Low load negative concrete; LNeuCon = Low load neutral concrete

interaction also was found when examining the effect of concreteness with negative and neutral words. In this case, there was an effect of concreteness with the negative but not neutral words. This pattern was found across all three time windows. Finally, there was a main effect of memory load, which occurred in the EPN and N400 windows, suggesting that even relatively early processing is affected by memory load.

In terms of the lower alpha results, the overall pattern was consistent with Klimesch et al. (2007). They suggested that

lower alpha desynchronization is a measure of memory and attentional use and is marked by effects that are topographically broadly distributed. In our case, the main effect of memory load was significant across all three time windows and occurred across most electrodes. A three-way interaction occurred across the three time windows and most electrodes. This appeared to be caused in large part by the negative concrete words showing more desynchronization in the high load compared with the low load condition, unlike the neutral

concrete words. There also was a similar effect in the EPN window, where the neutral abstract words caused significantly more desynchronization in the high load than the low load condition but the negative abstract words did not. Finally, the concrete words showed an effect of emotion in the N400 window in the high load condition, where negative words showed more desynchronization than neutral words, and an effect in the opposite direction in the low load condition in the LPC window.

These results suggest that concrete words have quite different processing demands compared to abstract words in terms of general memory/attention usage and the effect emotion has. The finding that the neutral abstract but not the negative abstract words were affected by memory load in the EPN window also is important. It suggests that if memory demands are responsible for the lack of EPN with concrete words, then the reverse pattern could potentially increase the effect with abstract words. In this case, rather than conceptualizing EPN as something that occurs simply on top of normal processing, the results could be conceptualized as reflecting the balance between the processing of emotional and neutral information. Why the neutral but not negative abstract words showed a significant effect of desynchronization due to memory load is less clear. One speculative possibility is that EPN causes early qualitative changes in the processing of emotional features in negative abstract words, which may result in fewer features being focused on compared with neutral abstract words. This in turn may mean less memory resources are used in processing and hence less desynchronization is found. Negative abstract words may attract additional attention away from the dual working memory task, which may allow them to be processed more easily.

The differences found with the concrete words in the different time windows with respect to emotion and memory load also gives some interesting insights into memory/attention usage. These results may again potentially be interpreted in terms of the balance between the processing of emotional and neutral information. In this case, if the level of desynchronization is reliant on the balance between the processing of negative and neutral information, and if working memory demands affect this, then negative concrete words may be disadvantaged compared to neutral concrete words in high memory load situations. That is, memory load may have had the effect of reprioritizing the balance between the processing of negative and neutral information with the concrete words. In this case, difficulties associated with the processing of negative concrete words may become magnified, especially if memory load blocks some of the processing advantages that affective stimuli might otherwise have (Miendlarzewska et al., 2013) with this type of word.

The pattern of memory effects also offers a potential explanation for the early interactions that were found and how they relate to other studies examining EPN. In particular, our

results are most similar to those of Kaltwasser et al. (2013), where abstract words showed the greatest effects of emotion. Unlike the study of Kaltwasser et al., however, our results showed an EPN effect whereas they first found differences in a later window. Their explanation for the differences between their study and others was that their experimental task had higher processing demands. Our results show this explicitly as we manipulated memory load. More importantly, our results showed the extent to which memory/attentional usage, as measured by lower alpha desynchronization, is affected by both emotion and concreteness. In this case, memory load appeared to modulate the extent to which negative and neutral information was processed in negative concrete and neutral concrete words. In particular, when negative concrete words were presented in high load conditions, they caused more alpha desynchronization than neutral concrete words, whereas only a null effect (EPN and N400 windows) or the reverse pattern (LPC window) was found in the low load condition. Such results show that understanding how memory load interacts in the processing of emotion with concrete and abstract words is important and offers support for claims that task demands are likely to be an important factor in different results that different studies have produced.

The results of the upper alpha data offer further insight into how effects of emotion may emerge. The data also looked as predicted by Klimesch et al. (2007); there were no main effects of memory, and the other differences were more topographically localized than the lower alpha results. In terms of emotion, there was an interaction caused by the concrete and abstract words showing results that went in the opposite direction of each other in the EPN and N400 windows, although only the abstract words in the N400 window showed an effect of emotion by themselves. Given these results are from upper alpha, this provides support for early interactions between concreteness and emotion that are to do with semantic processing. There were also later effects of emotion, with a main effect found in the N400 and LPC windows as well as a significant emotion by memory load interaction in the LPC window. The interaction appeared to be caused by words in the high memory load condition showing a significant effect of emotion, with more desynchronization occurring with the negative words. This result is consistent with the lower alpha results that suggested the balance between the processing of emotional and neutral information is important. In this case, the high load condition may have caused emotional processing to be prioritized over the processing of neutral information, even if it made overall processing more difficult. Negative stimuli therefore may have been processed to a greater extent than the neutral ones, hence causing a greater amount of desynchronization to be found.

Overall, the three different types of analyses provide convergent evidence for abstract words being processed differently to concrete words and that this is likely to be caused by

quite general processing constraints (memory and attention) and how they interact with the processing of semantics. In particular, the effect of emotion was consistent with the ERPs across all three time-windows. This included when comparing negative to neutral words, where there was a significant interaction between concreteness and emotion, and when comparing concreteness, where the effect was restricted to negative words. A strong memory load effect also was found in the EPN window and a weaker one in the N400 window. Whilst the memory effects with the ERPs did not interact with either emotion or concreteness, the opposite was found with the alpha desynchronization results, where there were strong effects of memory load, and these interacted with both emotion and concreteness in the lower alpha band. These results suggest that negative concrete words are processed quite differently than other types of words, using more general memory and attentional resources. Finally, when the lower and upper alpha results are combined, they support the possibility that memory load changes the extent to which negative and neutral information is processed, and this includes interactions with semantic information from relatively early in processing.

Based on the idea that the early processing of the semantic features of concrete words is susceptible to memory demands, it is possible to offer an explanation for why EPN was only found with abstract words. In this case, memory demands may slow the processing of emotional features in the EPN window with concrete words. This means that a strategy change that might occur with abstract words where emotional features are focused on would not occur with concrete words.

A number of patterns in our data offer some support for the idea that a strategy change may have occurred with the abstract words and that EPN may have been blocked with the concrete words. First, the lower alpha desynchronization data showed memory load affected the negative concrete words across all time-windows and the neutral abstract words in the EPN window. This suggests that concrete words are affected early in processing by memory demands, which may reduce the strength of early effects that would otherwise be found. It also may suggest that negative abstract words can access attentional resources very quickly, such that their later processing is more resistant to memory load than neutral abstract words. Thus, at least the precursors necessary for a strategy change appear to exist (i.e., the possibility of emotional features causing privileged access to other resources). Second, with the ERPs, the emotion by concreteness interaction was found across all three time windows. This suggests that differences that appeared early in processing were relatively stable across different types of processing. This was despite other studies finding different results at different time windows. This suggests our particular results were relatively stable and thus potentially suggest that if processes associated with EPN cause attentional capture, then this capture may cause a subset

of features to remain prioritized across both semantic and later processing. Finally, the concreteness effect was restricted to negative words in the ERPs. Given differences between concrete and abstract words have been found a number of times when only neutral words are examined (Kounios & Holcomb, 1994; Zhang, Guo, Ding, & Wang, 2006), as well as when mixed neutral and emotional stimuli have been used (as reviewed in the introduction), the fact that differences were not found with neutral words despite strong differences with negative words suggests a potential strategy change in the way the features of the words were processed across the task. Alternatively, the concreteness effect could be weak compared with other studies because of the silent reading and dual task conditions. In this case, negative but not neutral words may have shown a concreteness effect because negative words may have processing advantages over neutral words.

More general reasons for the emotion by concreteness interactions

There are a number of potential reasons for how memory load could have affected the results to produce the pattern of results found. One is that concrete words rely on transfer across different parts of the brain to a greater extent than abstract words (Schack et al., 2003). If this causes more memory or attentional resources to be used with concrete words, then it could limit or slow the amount of processing that could occur with the emotional features of words, and hence reduce any early affective boost. A second possibility based on the embodied theory of Kousta et al. (2011) is that the distribution of features is important. In this case, if words have groups of features that are similar, they may potentially be advantaged in processing compared to when they have features that differ (Hoffman & Woollams, 2015). In particular, with negative concrete words, both sensory-motor and affective/linguistic features would need to be processed but the feature groups may inhibit each other. With abstract words, such differences would not occur as much due to the more limited feature distribution (i.e., fewer sensory-motor features). If the speed at which this process can resolve itself is slowed by memory/attentional demands, such differences could impede the processing of negative concrete words more than negative abstract words due to the different distribution of features. In our data, support for this comes from the lower alpha desynchronization results, which showed that negative concrete words had greater memory/attentional demands than other types of words from very early in processing and from the upper alpha results that showed semantic processing was likely to be involved in this. This might represent feature processing and integration difficulties, thus delaying or reducing processing that may otherwise have occurred due to the emotional features. Finally, as noted in the *Introduction*, abstract words may simply have qualitative differences compared to concrete words. Thus,

negative abstract words may simply be less affected by working memory demands and hence more likely to produce EPN even under high memory load.

Unresolved issues and limitations

An interesting aspect of the results that remains unexplained is that whilst the negative concrete words showed a strong effect of memory load in the lower alpha desynchronization data, the overall level of desynchronization caused by the negative concrete words in the low load condition was very similar to some other groups. Thus, whilst memory load may provide an explanation for why the negative concrete words presented in high load conditions did not show EPN, it does not obviously explain why the negative concrete words in the low load condition also did not.

One possible explanation is that the low load condition still caused strong enough demands on processing such that its effect on processing was more similar to the high load condition than a no-load condition would have been. Indirect evidence for this can be found by comparing the results with other similar studies that did not use a dual working memory task. In this respect, the ERPs in this study in the low and high memory load groups were relatively similar but were quite different compared with another study that used a similar participant group and the same EEG system (Perry, 2018). In those experiments, an animal decision task was used with no dual-task. The results showed a pattern where the amplitude differences between the peaks were much greater than this experiment. This difference is similar to studies that have parametrically manipulated memory load within the same experiment (Lefebvre, Marchand, Eskes, & Connolly, 2005). This provides empirical evidence that suggests that even our low memory load condition was relatively demanding. This difference also may have been exacerbated by the silent reading conditions we used. In this case, participants may not have allocated as many resources to the processing of the words compared to the working memory task than if a task that forces each word to be more deeply processed was used (e.g., lexical or semantic decision).

In terms of limitations, there were a number of constraints on the task due to practical considerations. First, only negative words were used, whereas EPN occurs with both positive and negative words. This was done so the experiment could be run within a timeframe that minimized participant fatigue. Second, additional nonnegative fillers were added, which made the task longer. This was done to reduce strategic effects caused by participants realizing many of the stimuli were of negative valence, as well as to reduce the number of high arousal items that directly followed each other. Third, a silent reading task was used, which may have reduced effects as discussed above.

Conclusions

The current study investigated the extent to which EPN is modulated by phonological working memory load. The results suggest that phonological working memory load does not consistently modulate EPN with both concrete and abstract words, but rather, negative concrete words are more susceptible to working memory demands than negative abstract words. This result was somewhat surprising given that the representations of abstract words have been hypothesized to have greater linguistic content than concrete ones, and thus we had expected them to be more affected than concrete words by a high phonological working memory load.

The results are surprising from an ecological perspective: whilst it is not impossible to think of abstract concepts that might need to be acted on quickly, many things that do require immediate action, such as fear-related stimuli (Vuilleumier, 2005) tend to be concrete, as are pictures that have elicited EPN. For example, our stimuli included the words venom, hijackers, and arsenic as concrete words, the real versions of which might require an especially fast response, and misery, jealousy, and infidelity as abstract ones, none of which are likely to require an especially fast response. Thus, one might have expected an asymmetry in the opposite direction. This suggests that the reasons for our results are likely to do with how working memory affects semantic processing rather than something deeper based on the type of stimuli that have ecological significance and possess a need to be processed quickly. It highlights the importance of understanding how semantic representations interact with each other and affect behavior over time (Lambon Ralph et al., 2017) and the role that affective information has in this.

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